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Power Supply: The Railway Load

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1. Introduction

1.1 An electric railway system requires power supplies at various points along the track, the number and capacity of which depends upon the voltage regulation along the track and the type of system employed. If the supplies are given from generating stations solely provided for supplying the railway load, a network of transmission lines is required between those generating stations and the points of supply to the track, but if supplies are given from a transmission system, such as the Grid, interconnecting generating stations provided to supply both the railway load and the distribution system loads, then the private transmission system can be partly or wholly eliminated. This transmission system was partly eliminated in the scheme for supplying the London, Brighton and South Coast Railway in the 1930's, the Southern Railway only providing the interconnectors between the Grid supply points, off which tappings were made to supply intermediate track rectifier substations. Adoption of the 25 kV single-phase system for the electrification schemes proposed in the railway plan was contingent on the availability of supply points reasonably close to the track at every 25 to 30 miles on the main lines, on a high standard of security of supply being afforded, and on there being no adverse effect of the load on the supply system.

2. Points of Supply

2.1 The transmission system of the Central Electricity Generating Board consists of a primary network of 275 kV lines, the main function of which is to provide interconnection between the important load centres and the sources of generation to enable pooling of generating plant and bulk transmission of power to be effected. It also consists of a number of secondary systems of 132 kV lines generally radiating from the points of transformation to the 275 kV system, from which tappings are made to supply the Electricity Boards in bulk.

2.2 The South of Scotland Electricity Board has a similar system of primary and secondary lines and there is interconnection between the primary and secondary systems of the two Boards.

2.3 In the London area there is a 66 kV cable system which functions in the same way as the 132 kV system and there is a considerable amount of generation at distribution voltages of 33 kV and lower.

2.4 The bulk supplies to the distribution systems at each point of supply are provided, generally by duplicate transformers in sizes ranging from 30 MVA to 90 MVA capacity. These are connected to the transmission lines at switching stations in a variety of ways, examples of which are the one-switch station in which the transformers are teed off the lines through isolators and are switched on the lower voltage side to the distribution switchboard, the single H.V. switch being a section switch between the two lines; and the three-switch type in which the isolators connecting the transformers to the lines in the one-switch station are substituted by switches. Where supplies are given from a double busbar switchboard transformers are separately switched on the H.V. and lower voltage sides. Transformers may be banked together to form a parallel arrangement or to feed separate lower voltage switchboards. The connections between the transformer and the H.V. isolators or circuit-breakers may be short, such as when the transformers are located on the substation site, or long, in which case these circuits are known as transformer feeders.

2.5 Full discriminative protection is provided for the lines, transformers and busbars, and where the transformers are connected direct to the line through isolators intertripping is provided to trip the switch at the remote end of the line either through the medium of a pilot wire or by fault-throwing switches connected to the transformer H.V. terminals.

2.6 The short-circuit levels on the 132 kV side of the Grid transformers may vary between 1,000 MVA and 3,500 MVA, while on the lower voltage they may vary between 250 MVA and 1,000 MVA. With growing public loads it is necessary to reinforce supplies to the distribution systems either by replacing the transformers by larger units or by creating new points of supply. The transmission switching stations are controlled from continuously attended generating station control rooms or transmission control rooms, and in some cases automatic operation is provided to reclose switches which have tripped due to transitory faults on the lines such as lightning. All switching operations are directed from Grid Control Centres of which there are seven situated in England and Wales and one in the South of Scotland.

2.7 From the above it is seen that for supplying the railways there is a choice of giving supplies either from the 132 kV bars or lower voltage bars at Grid substations. In the former case the short-circuit level would be higher but the switching costly and complicated. With the latter the short-circuit level would be less but switching would be simpler and less costly; moreover, the Grid transformers would be common to both the railway load and distribution load and so the railway load would be subjected to some extent to changes that might take place due to reinforcement required on account of increase of the distribution load.

3. Security Requirements

3.1 With the 25 kV single-phase railway system it is essential that the security arrangements to each point of supply should be of a high order, especially where no permanent parallel operation is permissible between supply points through the catenary system. For parallel operation through the catenary system to be acceptable there should be no through flows which would cause unbalanced conditions on the transmission system. In general, sections of the 132 kV Grid are based on 275 kV points of transformation and permanent coupling between points on adjacent 132 kV systems has many technical and operational disadvantages. Furthermore, if it were considered necessary to connect single-phase transformers for the railway supplies at the various points of supply to different pairs of phases to produce some measure of balance of load, parallel operation through the catenaries would be prohibitive. It was therefore agreed with the Transport Commission that they would consider an arrangement between their supply points which only permitted change-over of load from one point to another through the catenary system involving a momentary break in the supply during the operation.

3.2 Experience of the Generating Board and South of Scotland Board in giving bulk supplies to the distribution systems by the methods which have been described has been very satisfactory over a period of operation of thirty years. In the case of the Generating Board supplies to the Southern Region, the average duration of failure of supply during a recent 5-year period was 2·4 minutes for 1·8 interruptions p.a., amounting to 0·004 minutes per million units supplied, which indicates the reliability which can be expected for the new railway loads.

4. The Effect of the Load

4.1 The two main factors to be considered in providing single-phase track supplies to the railways from the public supply system are unbalanced loads and harmonics. Unbalanced loads have three effects:

- (*a*) To cause unbalanced voltages which in turn produce unbalanced currents from balanced loads fed from the same source.
- (*b*) To restrict the capacity of the network to supply three-phase loads for distribution, and
- (*c*) To cause unbalanced current to flow in the generators producing overheating of the rotors.

4.2 Referring to the first effect, it is considered that the co-efficient of asymmetry of the voltage of a source of supply should not exceed 5 per cent. where the approximate co-efficient of asymmetry equals $\dfrac{\text{single phase load}}{\text{short circuit power.}}$ Applying this formula for a load of 20 MVA and 1,500 MVA on the 132 kV side, the co-efficient of asymmetry would be $1\frac{1}{3}$ per cent. At 33 kV a load of 5 MVA with 500 MVA on the 33 kV switchgear would give a co-efficient of asymmetry of 1 per cent.

4.3 Dealing with the second effect, where the load is small compared with the total capacity of the supply point, no undue restriction of capacity of the system would be significant on account of the single-phase loads. The use of Scott connected transformers was considered but it seemed that there would be no advantage in using them as they produce balanced conditions on the 3-phase system only if both windings on the 2-phase side are equally loaded, which would rarely occur in practice. Single-phase transformers are preferred on account of simplicity and cost, and on the busy railway system the loads taken along its length are expected to produce balanced conditions on the Grid as a whole if the single-phase transformers at the various supply points are supplied from different phases.

4.4 With regard to the third effect, experience has shown that generally a turbo-alternator should not supply continuously a single-phase load in excess of 10 per cent. of its nominal rating. The effect of unbalanced loads on the generators when the traction load is supplied from the Grid is not expected to be serious on account of spreading of the load between generators so that the proportion of negative phase sequence currents to positive phase sequence currents to which any one generator would normally be subjected would be small. However, if, due to special circumstances, the negative phase sequence currents were likely to be excessive this could produce overheating of the wedges in the rotors of generators connected close to the point of supply. Where such a condition is likely to arise negative phase sequence current alarms will be fitted on the generators on the receipt of which the output of the generator would have to be reduced while the special circumstances persisted.

4.5 Regarding harmonics, investigations in France have shown that the effect on the system of harmonics generated by rectification from single-phase systems differs little from that of harmonics generated by rectification from 3-phase systems if the third harmonic is suppressed. The effect of harmonics on the system may be to cause overloading of capacitors and other plant. As the harmonic voltages are proportional to the supply system impedance it is desirable to connect the traction load to supply points where the short-circuit level is proportionately high. It is therefore to be expected that there will be less interference with supplies taken direct from the 132 kV system than from the low voltage system. With regard to the third harmonic, a low impedance path will be provided in the delta windings of the transformers used for supplying the distribution systems.

4.6 Experience on the Lancaster – Morecambe – Heysham electrified line using single phase 6·6 kV 50 cycles per second alternating current supply from the North-Western Electricity Board's 6·6 kV system based at Lancaster, has not produced any unbalanced load or harmonic problems.

4.7 Summarising, it is not expected that there will be any difficulties in respect of unbalanced loads and harmonics, provided the larger single-phase loads are taken direct from the 132 kV system.

5. Method of Supply

5.1 So far, supplies have been put in hand for the following projects:—

(i) *Main Trunk Routes*

London (Euston) to Birmingham, Crewe, Liverpool and Manchester.

(ii) *Suburban Electrification*

London to Tilbury and Southend

London (Liverpool St.) to Enfield and Chingford

London (Liverpool St.) to Hertford and Bishops Stortford

Glasgow Suburban Lines.

5.2 For the Euston via Birmingham to Liverpool and Manchester main line, twelve points of supply will be given spread along the route generally from 25 to 30 miles apart, the firm capacity of each point varying from 5 MVA to 15 MVA. The proposed supply points are shown in fig. 1, and it can be seen that they are conveniently placed to the existing Grid systems.

5.3 At these supply points duplicate supplies are given and fig.2*a* shows a typical example. Two single-phase 132/25 kV transformers are banked each with the existing Grid transformer for supplying the distribution system. The railway transformers and distribution transformers have common arrangements for switching on the 132 kV side but have individually remote operated 132 kV isolators for easy isolation. 25 kV sides of the railway transformers are provided with isolators and earthing switches and connected to the railway substation by double-circuit 25 kV overhead line where practicable, or otherwise by 25 kV cable terminating in 2×25 kV single-phase circuit-breakers on the railway switchboard. Where an overhead line connection is used a 25 kV circuit-breaker is also provided at the transformers. The two transformers at a supply point are supplied from the same pair of phases but at adjacent supply points the phasing would be different. At some of the Grid substations from which it is proposed to give a railway supply, transformers are already banked in pairs to supply the distribution system and at these stations too it is proposed to add the railway transformers by banking, thus in no case has it been necessary to provide 132 kV switches specially to control the railway transformers, resulting in a considerable saving of capital expenditure.

5.4 At each point of supply the railway supply transformers will be connected to the railway substation by a 2-core concentric cable with the outer core only lightly insulated. Pilot cables will be laid between the Grid and the railway substations to provide for pilot protection for the 25 kV cables or overhead lines, intertripping, metering and telephonic communication. Normal tariff metering will be provided at the railway substation and load indications will be relayed to the Grid supply station Control Room.

5.5 For the smaller supplies to be provided in London, transformers have been supplied from the distribution systems. In these cases the transformers will be controlled by separate switches or teed off other transformers. Transformers used will be either single-phase, 3-phase or Scott-connected, depending upon load conditions.

6. Notes on Plant and Equipment

(*a*) *Transformers*

6.1 The standard ratings and voltage ratios envisaged for the railway transformers are shown in Table A, and so far orders placed by the Generating Board, involving sixteen transformers, have been confined to 15 MVA and 7·5 MVA sizes, with a ratio of 132/25 kV, and 5 MVA with a ratio of 66/6·25 kV. Transformers supplied to the initial orders were provided with on-load tap-changing equipment covering a range of ± 10 per cent. in 14 steps of 1·43 per cent., but later units have been specified on the basis of off-circuit tappings covering the same range in 5 per cent. steps. Transformers supplied to orders placed by the South of Scotland Electricity Board cover 6×5 MVA and 2×10 MVA 132/25 kV transformers with off-load ± 5 per cent. tap changing in $2\frac{1}{2}$ per cent. steps.

6.2 Voltage test levels specified (see Table B) are in accordance with B.S.171 (1959), values appropriate to rated voltages of 25 kV and 6·25 kV being chosen on the basis of a nominal system voltage of 44 kV and 11 kV respectively. Unlike the standard 132 kV 3-phase transformers however, where graded insulation is employed, the line to line connection involves selection of uniform insulation in all cases. Further, due to the line to line connection and the consequent possibility of simultaneous lightning surges to both line terminals, the form of impulse test specified includes, in addition to the normal sequence of full and chopped waves applied to one terminal, a similar sequence of impulse voltage waves applied simultaneously to both line terminals.

6.3 The cooling of the transformer is natural oil circulation, type ON, in the form of detachable radiators connected directly to the tank except for cases where noise conditions require a separate radiator bank to facilitate enclosure. A new series of standard bushings have been developed for these transformers.

(b) Cables

6.4 A new design of concentric conductor oil-filled cable has been developed for the 25 kV electrification scheme. The straight-through joints used incorporate the conventional type of hollow core oil-filled construction, of the appropriate dimensions, for the inner conductor and dielectric. For the outer concentric conductor a copper tube is applied over the central section of the inner screen and the wires from each side are joined over the tube. Stress cones are applied over the lead sheath terminations and the reapplied dielectric over the outer conductor is in the form of an open tube supported by spacers. The cables are terminated in outdoor vertical sealing ends on which, in order to bring out the outer conductor, an extra insulated unit is added to the normal design. Cable lengths of the above cable have been made, joints and terminations developed and the full type approval tests specified by the Generating Board for pressure type cable systems have been successfully completed.

(c) Switchgear

6.5 Two of the types of switchgear to control the output of the 25 kV single phase grid transformers are located in the B.T.C.'s substations and are exactly similar, except for the protective arrangements, to the two types used by the Commission in their track-side substations as described in papers 29 and 30 respectively.

6.6 The third, when used, is located at the Grid substation and is of the conventional out door bulk-oil type rated at 250 MVA and with a current rating of 800 amps. The unit is also specified to be capable of interrupting up to 3,000 amps at 44 kV and to have a minimum power frequency withstand level of 100 kV r.m.s. and a minimum impulse withstand level of 250 kV peak. The circuit-breakers are solenoid operated.

(d) Protection and Earthing

6.7 With regard to earthing of the 25 kV system, as the outer conductor of the concentric cables and one terminal of other plant such as the voltage transformers have only light insulation, it is necessary to provide solid earthing which prevents an excessive voltage on the earthing side of the system under fault conditions and complies with Regulation 4 of the Electricity Supply Regulations 1937.

6.8 The transformers are provided with balanced earth-fault protection on both the H.V. and lower voltage sides, together with Buchholz, winding temperature and high voltage overcurrent protection. At the low voltage end of the Grid transformers there is provided directional overcurrent and overcurrent protection. Pilot wire balanced protection is provided for the 25 kV cables where railway and grid substations are separate.

6.9 Provision is made for connecting the railway substation by telephone to the local Grid substation and to the relevant Grid Control Centre.

7. Conclusions

7.1 The scheme that has been adopted for supplying the railway loads from the Grid systems of the Central Electricity Generating Board and South of Scotland Electricity Board is provided at the minimum of expenditure to the Railways and gives the same level of security as is afforded to the distribution systems. It is not anticipated that there will be any troubles on the distribution systems fed from the Grid and generators, due to the characteristics of the railway load. The magnitude of the railway load, even when fully developed, will not exceed 2 per cent. or 3 per cent. of the total load.

7.2 System tests are now taking place on the first section of line to be electrified with single-phase 25 kV 50 c.p.s. cycles per second alternating current. The test results will give more positive information on the technical problems involved, and this will be presented in the form of an Appendix to Paper 2.

Table A
Envisaged Standard Ratings and Voltage Ratios of Transformers

Ratio kV	132/25	66/25	66/6·25	33/6·25
	—	—	2·5	2·5
	5·0	5·0	5·0	5·0
Rating	7·5	7·5	7·5	7·5
MVA	10·0	10·0	10·0	10·0
	15·0	15·0	15·0	15·0
	20·0	20·0	—	—

Table B
Voltage Test Levels of Transformers

Rated Voltage kV r.m.s.		*Impulse Voltage Test Level kV p.*	*Power Frequency Voltage Test Level kV r.m.s.*
132	3 phase	550	230
66	,,	350	140
33	,,	200	70
25	1 phase	250	95
6·25	,,	95	28

SUMMARY

In the first section of the Paper a description is given of the transmission system of the Generating Board in England and Wales and of the South of Scotland Electricity Board, and the way in which the bulk supplies to the distribution system are reinforced to meet growth of load. The reasons why the railway loads are to be mainly supplied direct from the Grid rather than from the lower voltage sides of the Grid transformers are given. Security requirements are broadly discussed, together with the effect of the railway load on the supply system in causing trouble due to unbalanced effects and harmonics. Details are given of the proposed arrangements of supply and of the plant and equipment to be used in the circuits supplying the railway load in bulk.

RÉSUMÉ

La première partie de cet exposé donne une description du réseau du Generating Board en Angleterre et au Pays de Galles et de celui du South of Scotland Electricity Board, ainsi que de la manière dont l'alimentation massive du réseau de distribution est augmentée pour face faire à des accroissements de charge. Les raisons pour lesquelles les puissances des chemins de fer doivent être fournies directement du réseau national en général au lieu des côtés basse tension des transformateurs du réseau national sont indiquées. Les auteurs font allusion d'une façon générale aux exigences de sécurité, ainsi qu'à l'influence de la charge des chemins de fer sur le réseau d'alimentation qui peut causer des troubles dûs aux effets des déséquilibres et des harmoniques. On donne des détails sur les dispositions proposées pour les prélèvements monophasés ainsi que sur les installations et le matériel qui seront utilisés dans les circuits qui devront fournir l'energie aux chemins de fer en grande quantité.

ZUSAMMENFASSUNG

Im ersten Abschnitt dieses Berichtes ist eine Beschreibung des Verteilungs-Systems der " Generating Board " in England und Wales und der " South of Scotland Electricity Board " gegeben; die Art und Weise, auf welche die Stromlieferung in das Verteilungsnetz verstärkt wird, um einer Zunahme der Belastung Rechnung zu tragen, wird erläutert. Die Gründe, warum der Strombedarf der Eisenbahn in der Hauptsache direkt vom Hauptnetz und nicht von der Niederspannungsseite der Netztransfomatoren gedeckt wird, sind angegeben. Die erforderlichen Schutzmassnahmen, sowie die durch den Einfluss der Eisenbahnlast im Verteilungsnetz auftretenden, durch unsymmetrische Einwirkungen und von Harmonischen hervorgerufenen Störungen, sind allgemein besprochen. Einzelheiten der vorgeschlagenen Regelung der Versorgung, der Anlagen und der im Stromkreis für die Stromversorgung der Eisenbahn verwendeten Einrichtungen sind angeführt.

RESÚMEN

En la primera sección de este Estudio se hace constar una descripción del sistema de transmision de la Generating Board en Inglaterra y el Páis de Gales y de la South of Scotland Electricity Board, así como la manera en que se refuerzan los suministros en globo al sistema de distribución para satisfacer las exigencias en el crecimiento de la carga. Se consignan asimismo las razones por las cuales las cargas de los ferrocarriles han de ser provistas en su mayor parte directamente por la Red más bien que por los lados baja tensión de los transformadores de la Red. Se discuten en su amplio aspecto las necesidades de la seguridad, como igualmente el efecto de la carga de los ferrocarriles sobre el sistema de aprovisionamiento dando lugar a inconvenientes debidos a efectos no compensados y a armónicos. Se aportan detalles de las medidas a adoptar para el suministro y de las instalaciones y equipos a emplear en los circuitos destinados a proveer la carga en globo para los ferrocarriles.

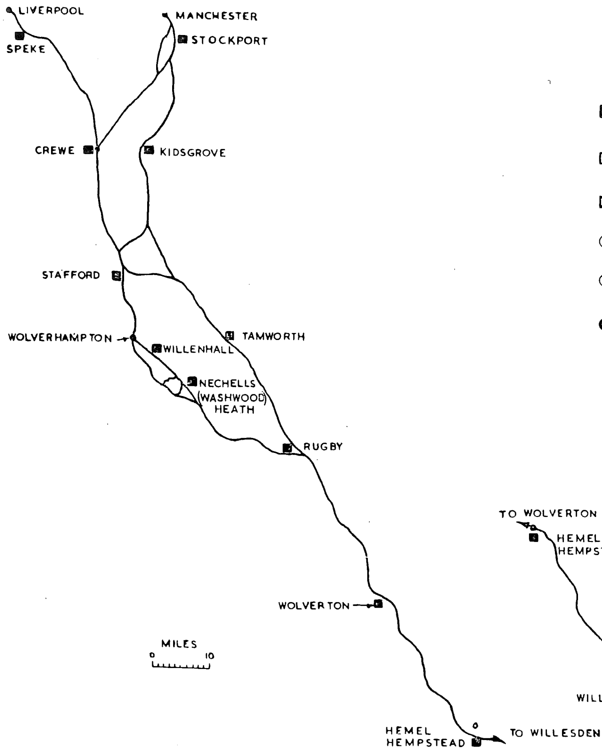
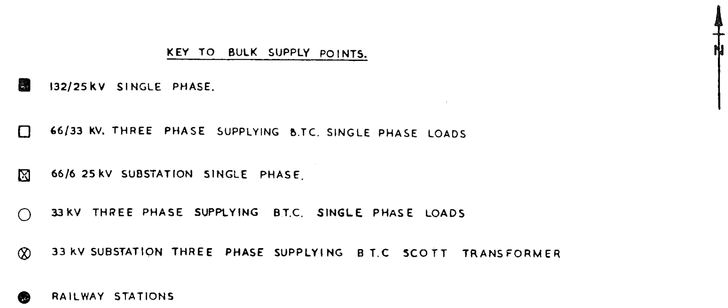


Fig.1(a) Euston-Manchester-Liverpool



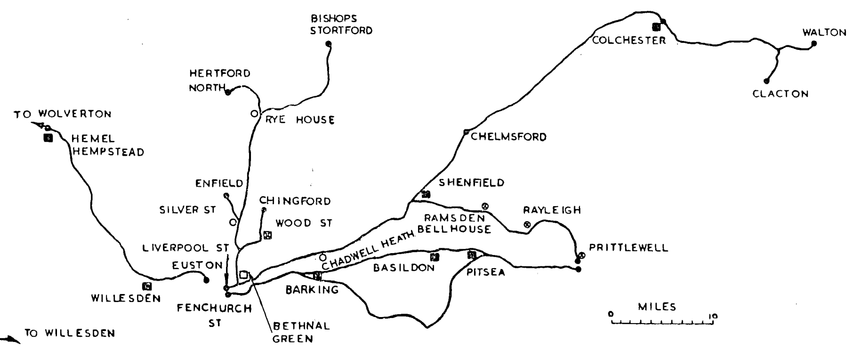


Fig.1(b) London and Suburban

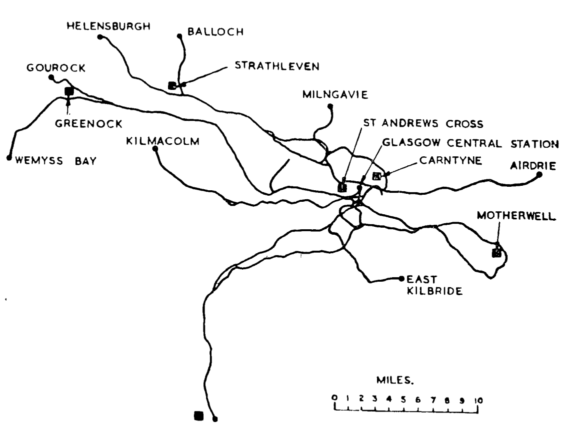


Fig.1(c) Glasgow and Suburban

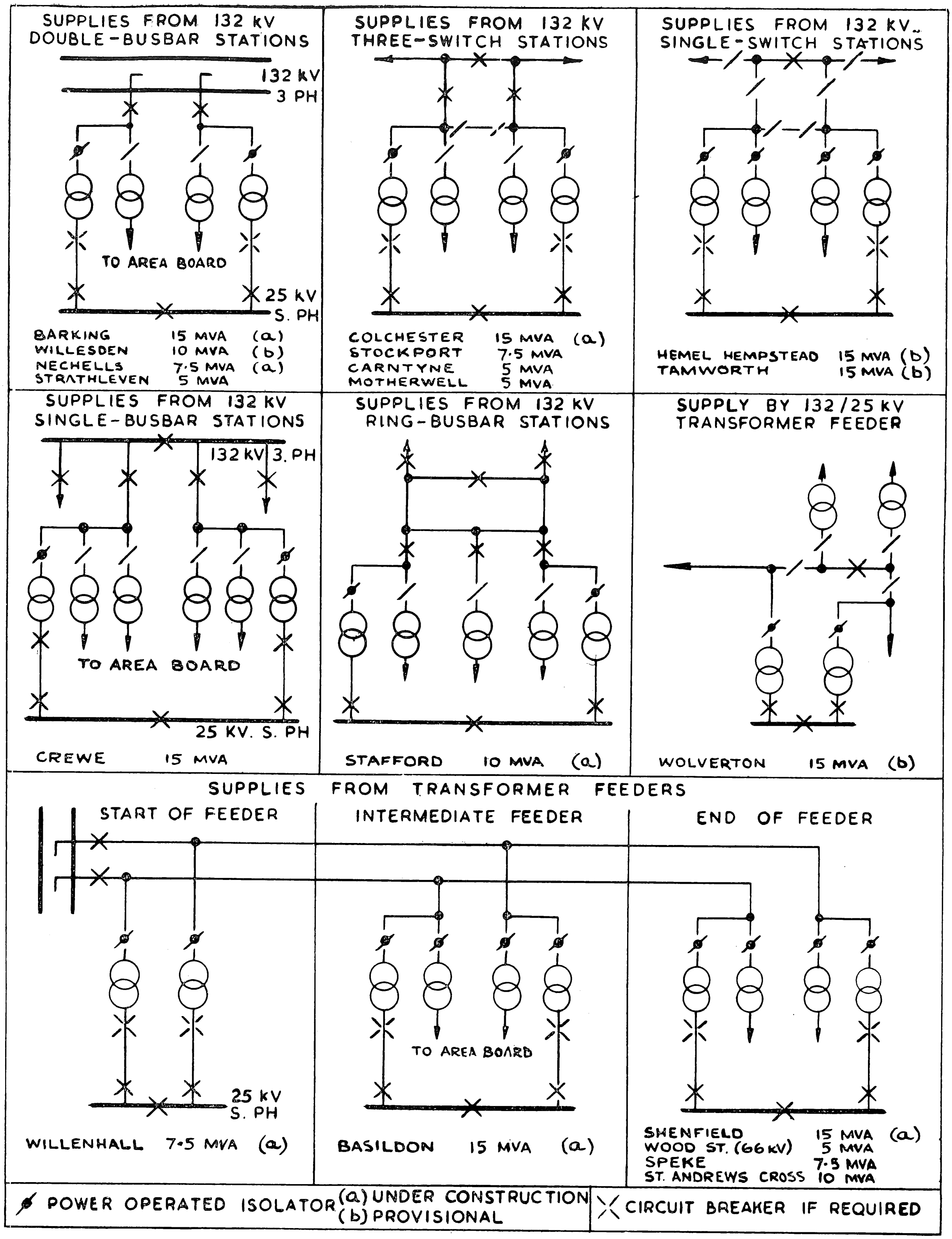


Fig.2 Typical supply arrangements

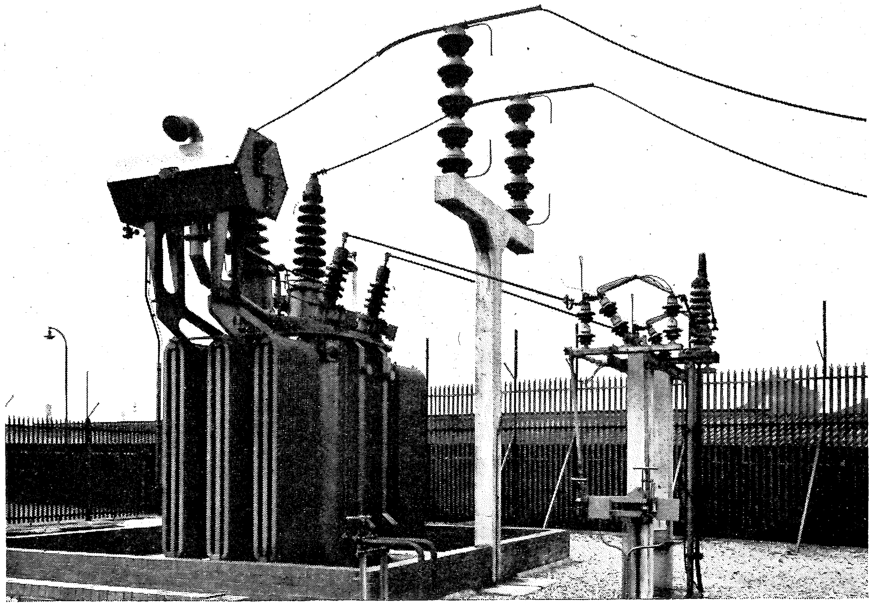


Fig.3 5 MVA 132/25 kV single phase transformer equipment at Corntyne

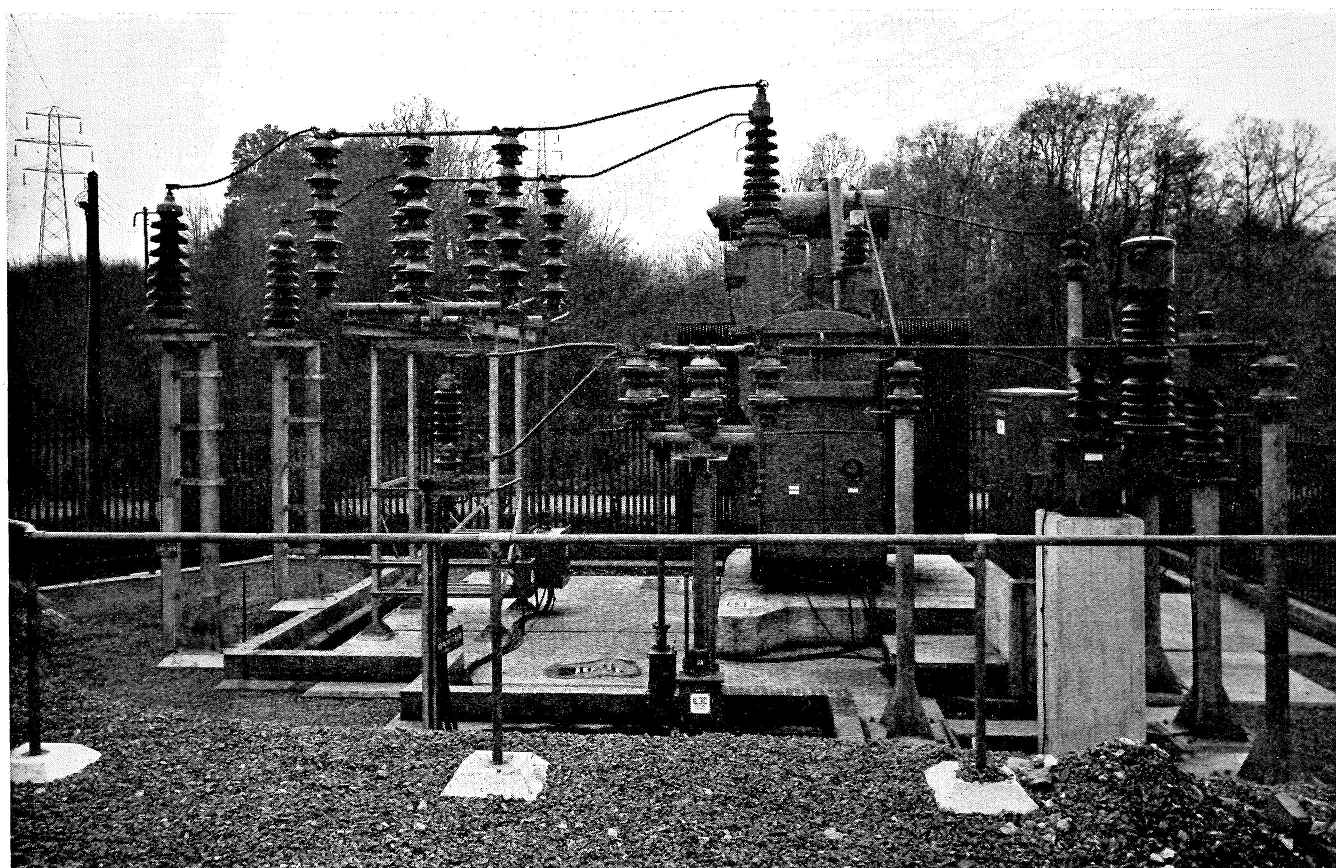


Fig.4 7·5 MVA 132/25 kV single phase transformer installation at Colchester

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